High-Energy 2-μm Laser Development

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Abstract- **The design and performance of a diode pumped Tm sensitized Ho $LuLiF_4$ (LuLF) laser oscillator and double-pass Tm:Ho:YLF laser amplifiers are described. The oscillator produced 135-mJ of Q-Switched output, which represents a slope efficiency of 0.09. To our knowledge this is the highest Q-Switched output for this material. The output energy of double-pass amplifier was improved by 75% compared to single-pass amplifier, and the energy extraction efficiency was increased from 1.4% to 3.1% at 54-mJ input pulse energy.**

I. INTRODUCTION

Space based wind sensing coherent Doppler lidar requires eye-safe, high energy, high efficiency, high beam quality, and single frequency laser transmitter. Solid-state 2-μm laser has been receiving considerable interest because of its eye-safe property and efficient diode pump operation. Recently, a relatively new host is showing a promising performance. This crystal involves using the same Ho and Tm ions doped in Lutetium Lithium Fluoride (LuLF) instead of the traditional Yttrium Lithium Fluoride (YLF). Quantum mechanical investigation of this material predicted that LuLF could perform better than YLF [1]. A maximum of 135-mJ output was obtained which corresponds to the optical to optical efficiency of 0.036 and slope efficiency of 0.088. To achieve high energy output while maintaining a high laser beam quality, a master-oscillator-power-amplifier (MOPA) 2-μm system is desired. The amplifier performance depends on the pump density; probe energy as well as the Ho, Tm doping concentrations. A double-pass laser amplifier was developed and compared with single-pass amplifiers. This paper describes the design and experiment results of this diode-pumped, room temperature 2-micron laser.

II. DIODE PUMPED HO:TM:LuLF OSCILLATOR

A. Laser Design

This laser is designed to produce 100 mJ of energy per pulse with a pulse length of 200ns. It operates around 2.053μm wavelength and is injection seeded to obtain single frequency. The laser is configured as ring oscillator with a length of 2.8 meters. Six mirrors, five flats and one curved with a curvature of 3 meter forms the resonator. Ring resonators narrow the emission line width since the spatial hole burning effect is minimized. The rod is positioned at the minimum waist with a TEMoo mode radius of 1.2 mm. The experimental setup is shown in Fig. 1.

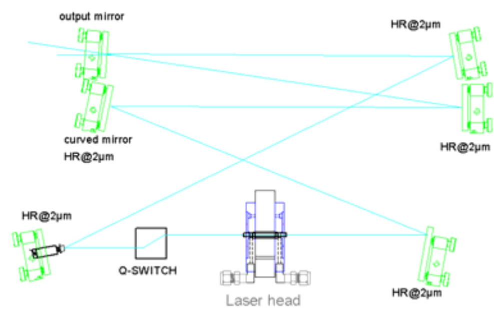

Fig. 1. Oscillator layout

A uniform side pump configuration is considered to minimize thermal gradient in the rod. The laser rod is side-pumped with 6 conductive cooled laser diode arrays. Each diode array has six bars with a spacing of 0.4mm between bars. The individual array can provide up to 600 mJ of pump radiation around 792 nm with 1ms pulse width. Three pairs of diode arrays placed 120 degrees apart around the circumference of the rod can thus provide a total of 3.6 J of pump energy. The diode lasers operate with electrical to optical efficiency of 0.42. The 4 mm diameter rod is liquid cooled inside a 6mm diameter fused silica flow tube. The tube also serves as a collimator to collect and direct the highly divergent pump diode laser radiation into the rod. The coolant temperature was set at 13 degrees Celsius.

Pump distribution measurement made on a similar laser head shows almost a flat top profile with only 30% higher intensity at the center. It was measured by probing the rod with a highly focused 543.3 nm laser beam, which is absorbed by Ho only. By scanning the rod with the probe beam while pumping the rod one can determine the relative Ho $^5I_7$ manifold population, thus the pump intensity, as a function of position [2]. The uniform pump distribution helps to acquire near diffraction limited beam quality.

The Ho:Tm:LuLF laser crystal is grown along the a-axis with 6% Tm and 0.5% Ho concentration. The length of the rod is 50 mm. Only the center 20 mm that is exposed to pumping is doped, the ends are diffusion bonded to 15mm undoped $LuLiF_4$ to facilitate the holding of the rod. The barrel of the rod has an antireflection coating for the pump wavelength of 792 nm, while the ends are AR coated for the emission wavelength of 2 μm.

A fused silica acousto-optics Q-switch with 24Mhz radio frequency is used in the resonator. This device is selected for its low loss and high damage threshold. The insertion loss is less than 0.02. The average power applied to this device is 4 Watts.

B. Experimental Results

Performance of the laser has been evaluated for four different output coupler reflectivities ranging from 0.66 to 0.82. In the free running mode the highest slope efficiency is .27 when a 0.79 reflectivity output coupler is used. However, to avoid the optical damage caused by strong internal circulating fluence, a 0.72 reflective mirror was selected in the final configuration. Using a lower reflectivity mirror has also helped to achieve a better Q-switch hold-off. In addition, higher seed laser power can be coupled into the resonator if injection seeding through the output coupler is considered, which makes the seeding process more stable.

Data is taken using two different output couplers. The result of the oscillator performance is summarized in table 1.

TABLE 1
Output energy at three various repetition rate and two output couplers

Repetition Rate (Hz)	Max. Q-S output with 66%R output (mJ)	Max. Q-S output with 72%R output (mJ)
2	105	135
5	96	116
10	68	97

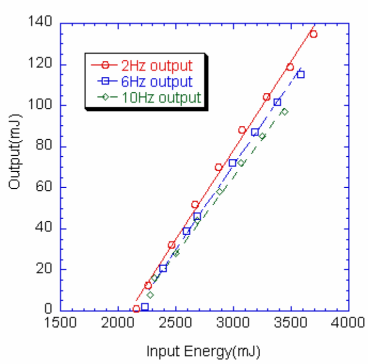

Fig. 2. Output as a function of pump energy for 72%R output mirror

The Q-S energy of the oscillator is shown in Fig. 2. At 2 Hz repetition rate, a maximum of 135-mJ output was obtained for input energy of 3.7 Joules, which corresponds to the optical to optical efficiency of 0.036 and slope efficiency of 0.088. The optical to optical conversion at 6 and 10 Hz are 0.032 and 0.028, while slope efficiencies are .082 and 0.075, respectively. Several factors contribute to the low efficiencies at higher repetition rate. First, the output of the pump lasers is reduced by 4% at higher repetition rate. Second, the wavelength of the pump lasers is broadened that can reduce the absorption. Third, the heat load on the rod is increased that affects the population inversion significantly.

III. Double-pass diode-pumped pumped Ho:Tm:YLF amplifier

A. Laser Amplifier System Configuration

The schematic diagram of the experimental setup for the double-pass amplifier is shown in Fig. 3, which is composed of a Tm:Ho:YLF laser oscillator, previously developed in a ring-cavity configuration and described in references [3], a Tm:Ho:YLF laser amplifier, and the required optical components.

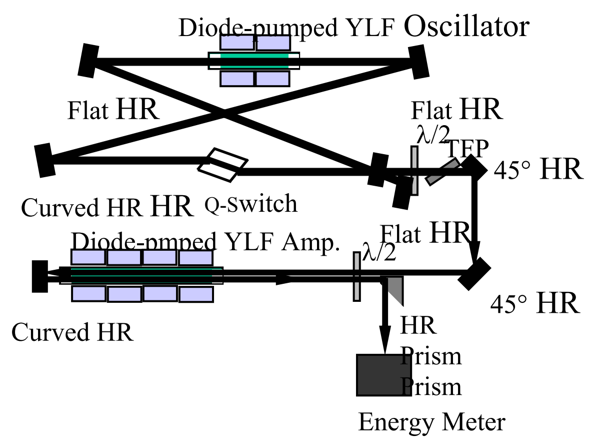

Fig. 3. Schematic diagram of experimental setup for a double-pass amplifier

The diode-laser-side-pumped Tm:Ho:YLF laser amplifier has similar pumping geometry to the laser oscillator. Twenty GaAlAs high-brightness stacked diode arrays at the wavelengths around 792 nm could deliver a peak power of 360 × 20 W to a 40 mm length Tm:Ho:YLF laser crystal rod. The amplifier was located at 1 meter away from the output coupler of the laser oscillator and the size of probe laser beam from the oscillator was around 2.0 mm in diameter. The c-axis of the amplifier YLF rod was corsely aligned paralle to that of the laser oscillator, which is perpendicular to the drawing plane. A half waveplate was used for a fine ajustment to make the polarization of the laser pulses from the oscillator parallel to the c-axis of the Tm:Ho:YLF amplifier laser crystal, a birefregent material with highest gain along the c-axis.

For a single-pass amplifier, the laser output beam from the oscillator was directed into one end of the amplifier with two 45° high reflectors and the output pulse energy was directly measured at the other end of the amplifier. For a double-pass amplifier, the laser beam was reflected back into the amplifier after passing the amplifier with a slightly tilted curved high reflector. The radius curvature of the high reflector was determined as 3 meter to compensate the negative lens effect of the Tm:Ho:YLF amplifier rod. The reflected laser beam was totally seperateed from the beam into the amplifier at the location of 0.7 meter from the amplifier and was directed to the power meter by a coated prism.

B. Experimental Results

Fig. 4 shows the measured output pulse energy and the calculated gain of the amplifier as a function of the input pulse energy of the amplifier at the pump pulse energy of 6.5 J for both the sing-pass and double-pass cases. The gain was defined as the ratio between the output pulse energy, E_{out}, and the input pulse energy, E_{in}, of the amplifier. The output pulse energy increases as the input pulse energy increases, but due to the saturation, the gain of the amplifiers decreases with the increase of input pulse energy. The output pulse energy was saturated faster in the double-pass case than in the single-pass case because the total pulse energy in the laser crystal of the amplifier were much higher in the double-pass case. At the pump pulse energy of 6.5 J, the output pulse energy of 146 mJ and 256 mJ were achieved respectively for the single-pass and double-pass amplifiers with the input pulse energy of 54 mJ.

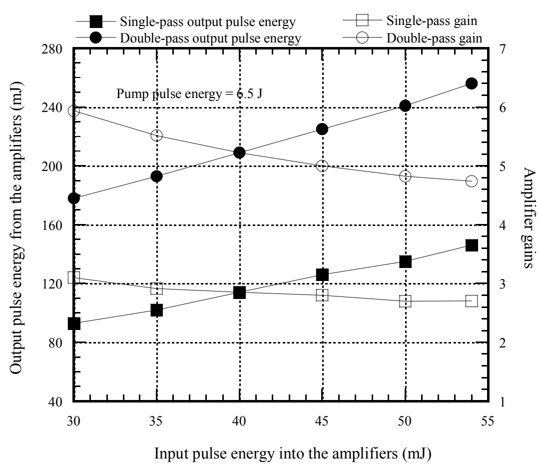

Fig. 4. Output pulse energy and the calculated gain as a function of the input pulse energy of the amplifiers

Double-pass amplifier or multiple-pass can help to extract more pulse energy from the amplifier in order to increase the output pulse energy and to improve the efficiency of the amplifier. Fig. 5 shows the pulse energy extraction efficiency, defined as $\eta = (E_{out} - E_{in})/E_{pump}$, as a function of the pump pulse energy for both single-pass and double-pass cases. The double-pass amplifier displays much higher extraction efficiency than the single-pass amplifier. It is also obvious that the extraction efficiency increases as the pump pulse energy increases. With more pump pulse energy coupled into the Tm:Ho:YLF laser crystal of the amplifier, the extraction efficiency might be further improved.

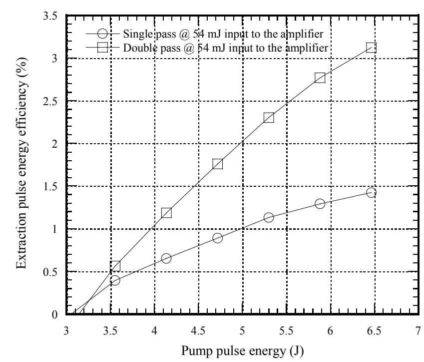

Fig. 5. Pulse energy extraction efficiency as a function of the pump pulse energy

IV. Conclusion

We have demonstrated a diode pumped room temperature Ho:Tm: LuLF oscillator with 135mJ of output energy. To our knowledge this is the highest energy published for this material. This laser can be used to detect tropospheric wind with a respectable range. A double-pass diode-laser side-pumped Tm:Ho:YLF laser amplifier at 2.05 µm has also been demonstrated. At the input pulse of 54 mJ and pump pulse energy of 6.5 J, initial experimental results have shown that for a double-pass amplifier, the output pulse energy reached 256 mJ, which is 75% higher than a single-pass amplifier, and the extraction efficiency was 3.1%, indicating a factor 2.2 of the extraction efficiency for the single-pass amplifier.

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